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Comparison between Laboratory and Field Expansion of Alkali-Carbonate Reactive Concrete

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COMPARISON BETWEEN LABORATORY AND FIELD EXPANSION OF ALKALI-CARBONATE REACTIVE CONCRETE

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Abstract: In the early 1980's, there was a recurrence of field problems with the alkali-carbonate reaction in concrete in eastern Ontario. At that time, it was noted that the expansion of concrete in the field appeared to be significantly greater than that of laboratory concrete made with the same aggregate and cement. To investigate this further, concrete sidewalk slabs were constructed outdoors in Kingston, Ontario. It was found that alkali-carbonate reactive concrete stored in the laboratory at 23°C does not expand as much as concrete in outdoor exposure. Storage in 5% NaCl solution or moist at 38°C will give a better idea of likely expansion of concrete slabs in the field after 5 years. Because of their larger surface area to volume ratio, concrete prisms stored in the laboratory generally lose significant amounts of alkalies compared with concrete in field exposure. Cracking due to the alkali-carbonate reaction resulted in average compressive strength losses of 45% after 5 years. The use of 50% substitution of ground granulated blast-furnace slag (ggbfs) cement did not reduce expansion sufficiently so that alkali-carbonate reactive aggregate could be safely used. The rate of field expansion was constant for ggbfs mixtures, whereas for Portland cement concrete the rate decreased significantly after one to two years.

Résumé: Au début des anneés 1980, on a noté dans l'Est de l'Ontario, une résurgence des problèmes causés sur le terrain par la réaction alcali-carbonate. On avait remarqué, à cette époque, que la dilatation du béton sur le terrain était beaucoup plus importante que celle enregistrée en laboratoire sur le béton composé des mêmes types d'agrégats et de ciment. Pour approfondir cette question, on a fabriqué en plein air des dalles de trottoir de béton à Kingston, en Ontario. On a constaté que le béton réagissant aux alcalis et au carbonate et entreposé en laboratoire à une température de 23°C ne se dilate pas autant que le béton exposé aux éléments. L'immersion du béton dans une solution de NaCl à 5% ou son entreposage dans un endroit humide maintenu à une température de 38°C permettra de mieux prévoir la dilatation des dalles de béton sur le terrain après cinq ans. En raison de leur plus grand rapport superficie/volume, les prismes de béton entreposés en laboratoire perdent généralement beaucoup plus d'alcalis que le béton exposé aux éléments. La fissuration attribuable à la réaction alcali-carbonate a entraîné une perte moyenne de résistance à la compression de l'ordre de 45% après cinq ans. L'utilisation de béton composé de 50% de laitier granulé de haut fourneau n'a pas réduit la dilatation de façon suffisamment importante pour permettre l'emploi sécuritaire d'agrégats réagissant aux alcalis et au carbonate. Le taux de dilatation sur le terrain des mélanges de laitiers granulés de haut fourneau était constant, tandis que celui du béton de ciment Portland avait diminué considérablement après un ou deux ans.

Keywords: aggregates, performance, concrete, alkalies, Portland cement, testing, alkali-aggregate reaction, expansion, cracking, slag cement

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COMPARISON BETWEEN LABORATORY AND FIELD EXPANSION OF ALKALI-CARBONATE REACTIVE CONCRETE

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Alkali-carbonate reactive concrete stored in the laboratory at 23°C does not expand as much as concrete in outdoor exposure. Storage in 5% NaCl solution or moist at 38°C will give a better idea of likely expansion of concrete slabs in the field after 5 years. Because of their larger surface area to volume ratio, concrete prisms stored in the laboratory generally lose significant amounts of alkalies compared with concrete in field exposure. Cracking due to the alkali-carbonate reaction resulted in average compressive strength losses of 45% after 5 years. The use of ground granulated blast furnace slag [GGBFS] at 50% did not reduce expansion sufficiently so that alkali-carbonate reactive aggregate could be safely used. The rate of field expansion was constant for GGBFS mixtures, whereas for Portland cement concrete the rate decreased significantly after one to two years.

INTRODUCTION

In the early 1980's there was a re-occurrence of field problems with the alkali-carbonate reaction in eastern Ontario. This was caused by the failure to properly test recently opened lower benches in a dolomitic limestone quarry supplying concrete coarse aggregates [1]. At the time it was noted that the expansion of concrete in the field, although not measurable accurately, appeared to be significantly greater than that of laboratory concrete made with the same aggregates and cement. To investigate this further, concrete sidewalk slabs were constructed outdoors in Kingston, Ontario, Canada in the summer of 1985.

EXPERIMENTAL PROCEDURE

Construction

Four sidewalk slabs of air-entrained concrete were constructed with a highly expansive alkali-carbonate reactive coarse aggregate and a variety of cements. Each slab was 1.2 m by 3.7 m and 0.2m thick, and was placed on a crushed stone base. The concrete was proportioned by mass and mixed on site using a 0.17m^3 mixer. Details of the cement alkalies and concrete properties are shown in Table 1. Slab 3 was made with ground granulated blast furnace slag cement substitution (ggbfs) for the high alkali cement used in Slabs 1 and 4. Slab 3 was divided into two parts, one with 25% ggbfs identified as Slab 3.1 and the other with 50% ggbfs identified as Slab 3.2. All mixtures were proportioned with 310kg/m^3 cement with a stone to sand ratio of 60:40 by mass. Stainless steel bolts were set in the plastic concrete and subsequently measured with a 0.50m Whitemore strain gauge. The slabs were cured with wet burlap for four days. Following curing, an asphaltic concrete apron was placed around each slab, flush with the concrete surface.

One week after curing, a series of measurements was taken over a period of several days to establish a zero reading to measure subsequent expansion.

Table 1 - Summary of Concrete and Cement Properties

	Slab 1	Slab 2	Slab 3.1	Slab 3.2	Slab 4
Air content in plastic concrete	6.0 %	5.75 %	-	5.5 %	7.6 %
Slump in mm	70	70	-	70	80
Effective water/cement	0.57	0.52	0.51	0.54	0.53
Cement alkalies:			25% ggbfs	50% ggbfs	
Na_2O, %	0.62	0.34	0.32	0.32	0.62
K_2O, %	0.63	0.34	0.53	0.53	0.63
Equivalent Na_2O, %	1.04	0.56	0.67	0.67	1.04
			Note 1	Note 1	Note 2
Alkali content of mix as Na_2O equivalent in kg/m^3	3.22	1.74	2.95	2.65	3.88 Note 2
Water Permeability, 6 years, m/s	4×10^{-8}	2×10^{-10}	2×10^{-7}	6×10^{-9}	3×10^{-9}
Strength, MPa					
Compression, 28 days	32.0	39.8	30.3	37.0	25.9
Compression, 6 years	15.9	21.8	13.9	20.4	18.7
% loss in comp. strength	50	45	54	45	28
Splitting tensile, 6 years	1.82	2.19	0.93	1.29	1.61
% Tensile/compression	11.4	10.0	6.7	6.3	8.6

Notes

1 Data for ggbfs given; mixed with high alkali cement used in Slabs 1 and 4

2 NaOH added to mix water to boost alkali to 1.25% by mass of cement.

Materials

The coarse aggregate came from the upper 6m of the Pittsburg quarry in Kingston. This quarry is in a horizontal, medium bedded argillaceous dolomitic limestone of Middle Ordovician age and is highly alkali-carbonate reactive. The first description of alkali-carbonate reactivity by Swenson [2] was of concrete made with coarse aggregate from the same horizon in this quarry. The fine aggregate came from a local natural sand deposit containing rocks and minerals derived from Precambrian bedrock (quartz, feldspar, marble, and trace amounts of minerals such as garnet, amphibole and mica). The sand has been used for many years in high alkali cement concrete with no reported problems due to lack of durability.

Two Type 10 Portland cements meeting the requirements of CSA A5 were used. One was a low alkali cement from Woodstock, Ontario. The other was a high alkali cement from Bath, Ontario. A granulated blast furnace slag cement from Fruitland, Ontario was used in Slabs 3.1 and 3.2. An air-entraining agent was added to all of the mixtures.

Testing

The slabs were cast in an open area. During the winter there were frequent cycles of freezing and thawing with periodic dispersal of sodium chloride de-icing salt on the surface to remove ice and snow. The expansion of the slabs was monitored on a yearly basis using a Whitemore strain gauge. Measurements were taken at the same time every year (July) under temperature conditions similar to those at the time the zero

measurement was taken. This removed the problem of having to adjust for thermal expansion effects.

At the time of manufacture of the concrete, a number of samples were taken for laboratory testing: 75x100x405mm prisms for laboratory length change and 150x300mm cylinders for compression testing. The prisms from each mixture were assigned randomly to one of three storage conditions. Three prisms were stored uncovered in a moist curing room at 23 ± 2°C, three were immersed in 5% NaCl solution at 23 ± 2°C, and three were placed horizontally on top of each other, in a sealed steel box lined with filter paper with 20 mm of water in the bottom, stored at 38 ± 1°C. In the case of Slabs 3.1 and 3.2 there were insufficient prisms to store in all conditions. The prisms were periodically measured for length using the test procedure and equipment described in CSA test method A23.2-14A.

At an age of 6 years, 100 x 200 mm cores were removed from the slabs and subjected to a variety of tests. Pairs of cores were saturated in water for 48 hours, capped, and broken in compression. Another core was broken in split tension. The top 40mm of one core from each slab was tested in the water permeability apparatus described by Hearn and Mills [3]. Powdered samples were prepared from a variety of depths in a core from each slab, for determination of alkali profile using neutron activation analysis. The fragments from the tensile splitting test were crushed, powdered to pass 75 µm and analysed for acid and water soluble alkalies using the technique described by Rogers and Hooton [4]. One laboratory length change beam from each storage condition was removed and the middle 1/3 obtained by cutting with a saw. The concrete was crushed, dried overnight at 60°C, and a powder prepared and analysed for alkalies.

RESULTS AND DISCUSSION

Figures 1 to 5 show the expansions of the laboratory and field concretes from each mixture stored under a variety of conditions. Storage at 38°C over water invariably resulted in the most expansion. Storage in the conventional moist curing room at 23°C invariably gave the least expansion after five years. The present CSA standard specifies storage moist at 23°C as the test for determining potential for deleterious expansion due to the alkali-carbonate reaction. For this environment, the specification is currently set at a maximum of 0.025% at one year. All of the concrete mixtures failed this requirement. Up to an age of about one year, expansion under moist storage at 23°C is similar to that obtained in the field. Beyond one year the rate of laboratory expansion decreases faster than field expansion. Clearly, this test is not ideal for estimating likely long term expansion. It also confirms the earlier suspicion that laboratory expansion underestimates field expansion of concrete affected by the alkali-carbonate reaction. This observation is confirmed in part by Mielenz and Witte [5] who found that outdoor exposure of slabs of alkali-reactive concrete showed considerably greater distress than moist cured specimens.

Figures 6 and 7 show the water soluble potassium oxide and sodium oxide equivalent remaining in the concrete after 6 years. It can be seen that, in general, the amount of alkalies remaining in the concrete stored moist at 23°C was significantly less than that of the concrete in outdoor exposure. It is believed that this loss was caused by leaching of the alkalies out of the laboratory concrete. This mechanism had been suspected at the time of construction of the slabs. In an effort to alleviate this leaching, one set of prisms was stored in 5% NaCl solution. The alkali content, expressed as Na_2O equivalent, of these prisms was higher than that of the field concrete. The field expansion of Slabs 1, 3.1 and 4 (Figures 1, 3, and 5) was greater than but similar to that of the prisms stored in the NaCl solution. It is postulated that the cracking of concrete promotes leaching of

alkalies in the laboratory, and that the most severely cracked concretes will lose the most alkalies under a given condition.

The analysis of progressively deeper slices below the surface of the slabs showed that below a depth of about 9 mm the distribution of alkalies was remarkably constant. In the upper 6 mm there was a 58% increase in Na_2O, presumably mainly derived from de-icing salt spread on the surface over the previous five winters. There was also a 17% increase in K_2O in the upper 6 mm. This may have been due to concentration by evaporation of pore water containing alkalies at the surface.

The slabs were in a location exposed to many cycles of freezing and thawing every winter. The concrete was adequately air-entrained. However, it is possible that freezing and thawing aggravated the expansion of the slabs by ice formation in the cracks initially caused by the alkali-carbonate reaction. In an earlier experience [1] it was found that within 5 to 6 years, concrete initially cracked by the alkali-carbonate reaction had disintegrated due to ice wedging in the open cracks. Air-entrainment will not protect concrete from ice wedging in open cracks. Thus the expansion measured in the field may not only be due to the expansion caused by the alkali-carbonate reaction but also may be due to wedging caused by ice formation.

The cracked concrete slabs showed a significant loss in compressive strength after 6 years (Table 1). There was an average of a 45% loss in compressive strength compared with cylinders tested at an age of 28 days. The compressive strength showed a significant correlation with the water permeability (Figure 8). Normally, mature, uncracked concrete with a w/c ratio of about 0.65 will have a water permeability of about 10^{-12} to 10^{-13} m/s. The permeabilities of the cracked concrete were orders of magnitude greater.

Soles *et al* [6] conducted a study of the effectiveness of blast-furnace slag cements in reducing expansion due to the alkali-carbonate reaction. They used aggregate crushed from a single bed from the upper 6 m of the Pittsburg quarry used in this study. They found that 40% ggbfs was effective at reducing expansion of concrete beams at ages of up to two years. Soles *et al* did note, however, that the rate of expansion did not appear to be reduced and that deterioration might occur at greater ages. In this present study, 50% ggbfs did give significant reductions in expansion at one year (77% in outdoor exposure and 60% moist at 23°C) compared with high alkali cement mixtures. After five years of outdoor exposure, the reduction in expansion using 50% ggbfs compared to high alkali cement was only 27% (13% when stored moist at 23°C). In Figures 3 and 4 it can be seen that the rate of expansion for the ggbfs mixtures in outdoor exposure was constant over the five years. In contrast, the high alkali cement mixtures showed a significantly reduced rate of expansion after one to two years (Figures 1 & 5).

CONCLUSIONS

Alkali-carbonate reactive concrete slabs in outdoor exposure at one year expand about the same as concrete prisms stored moist at 23°C in the laboratory. Thereafter, expansion in the field is greater than laboratory expansion at 23°C. The storage of concrete in 5% NaCl solution or moist at 38°C will give a better idea of likely expansion of concrete slabs in the field after 5 years, than storage in the conventional moist curing room at 23°C. Concrete prisms stored under moist laboratory conditions generally show a reduction in water soluble alkalies compared with concrete slabs in field exposure. Cracking of concrete due to the alkali-carbonate reaction significantly increases water permeability and results in average compressive strength losses of 45% after 5 years. The use of ground granulated blast-furnace slag in amounts up to 50% did not reduce expansion sufficiently so that alkali-carbonate reactive aggregate could be safely used. The rate of

expansion is constant for ggbfs mixtures, whereas for normal Portland cement concretes the rate decreases significantly after two years.

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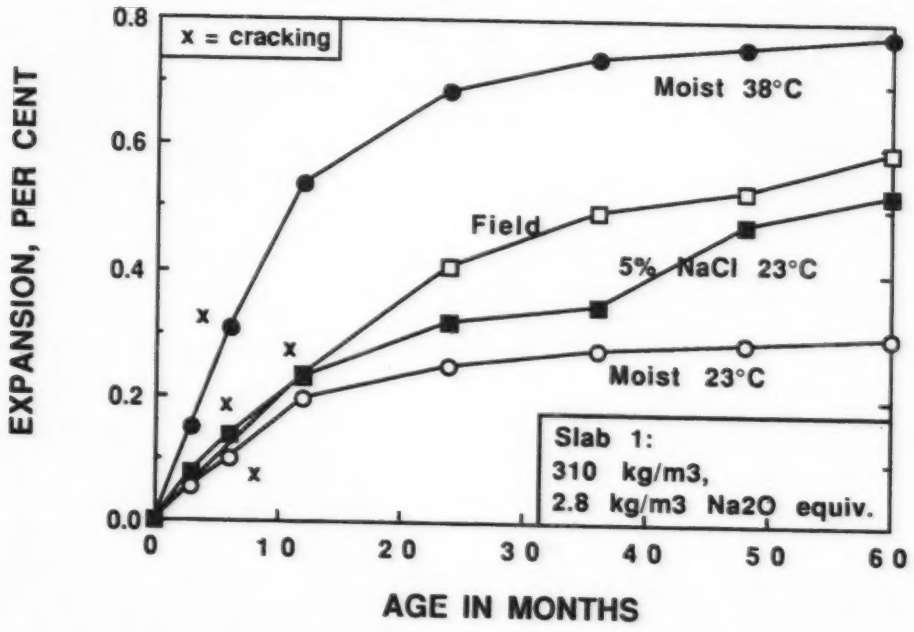

Figure 1 Expansion of concrete, Slab 1

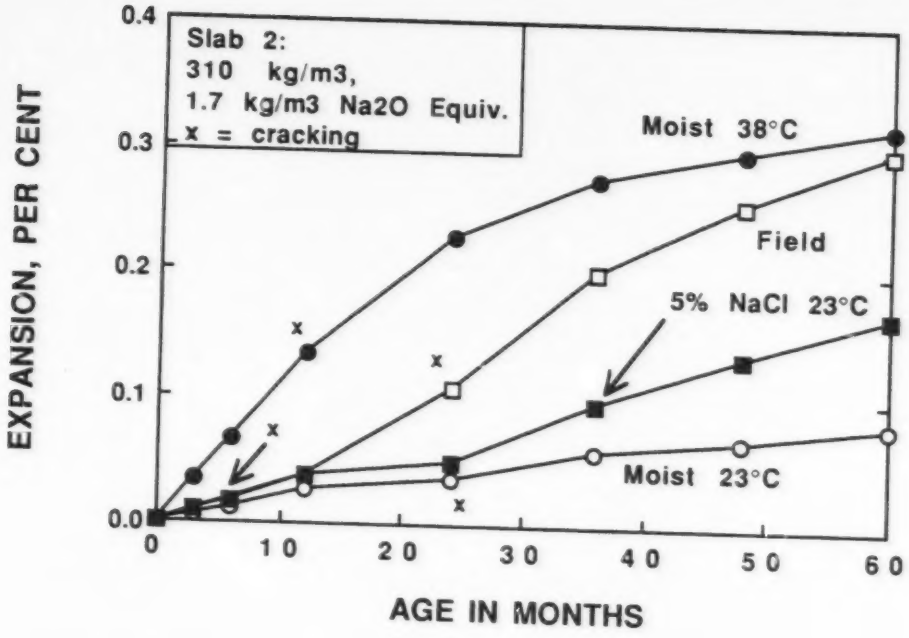

Figure 2 Expansion of concrete, Slab 2

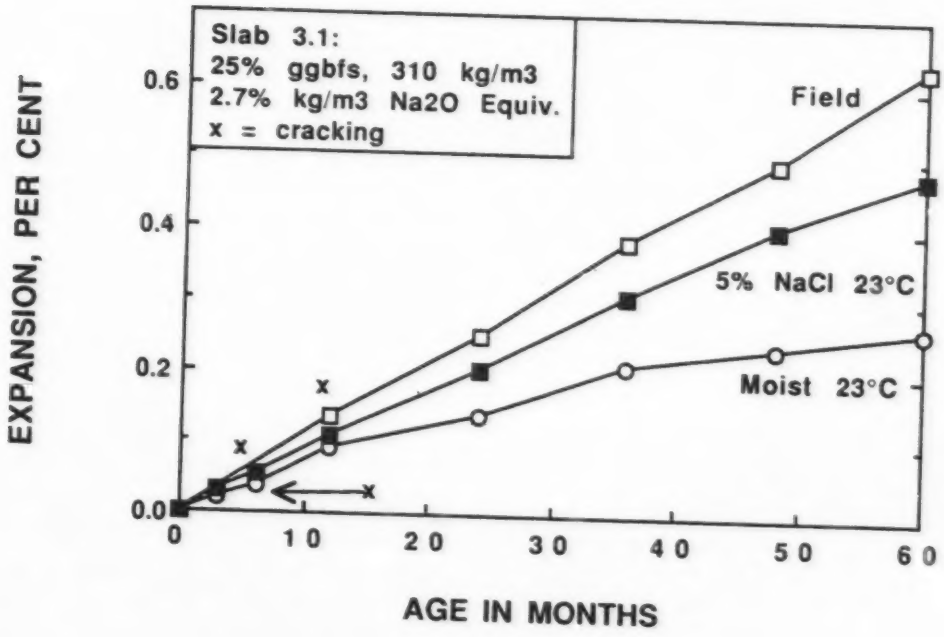

Figure 3 Expansion of concrete, Slab 3.1

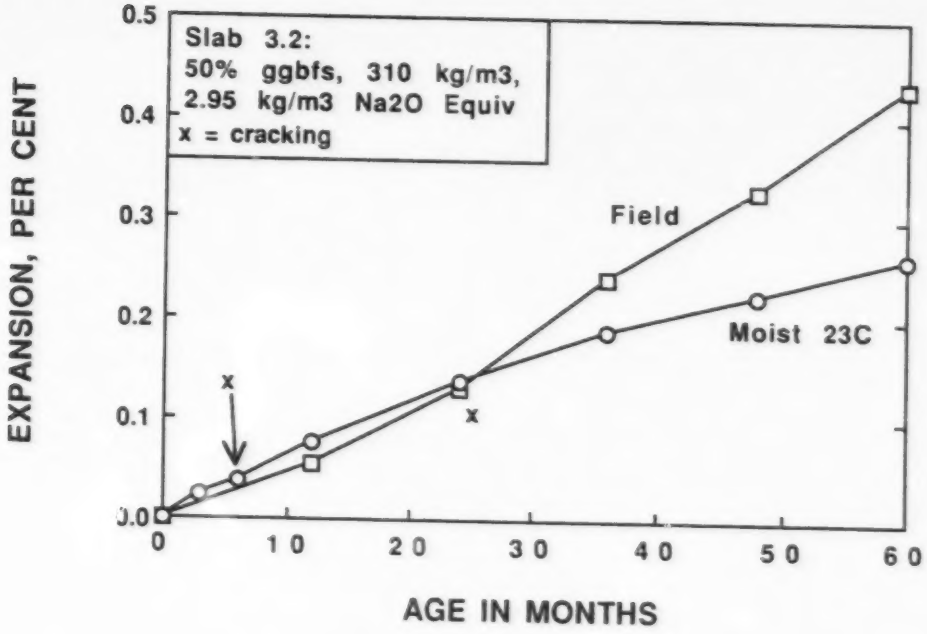

Figure 4 Expansion of concrete, Slab 3.2

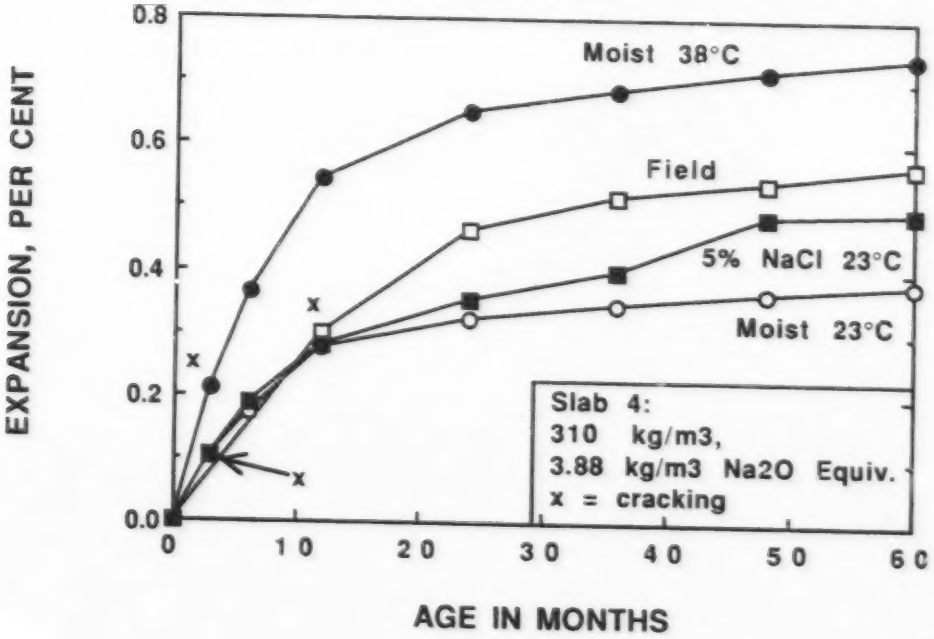

Figure 5 Expansion of concrete, Slab 4

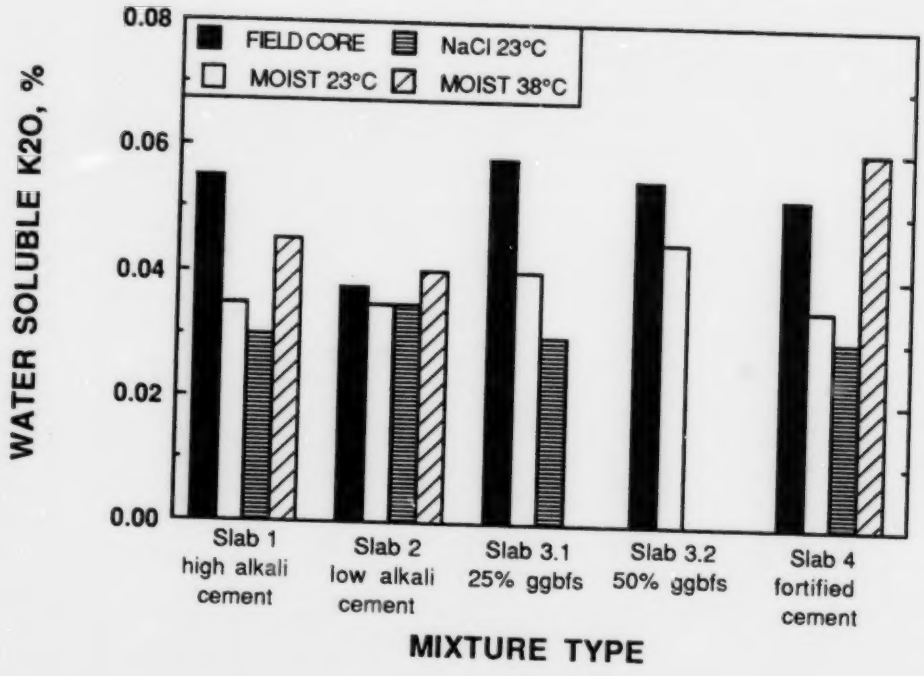

Figure 6 Water soluble Potassium Oxide in the concretes after six years

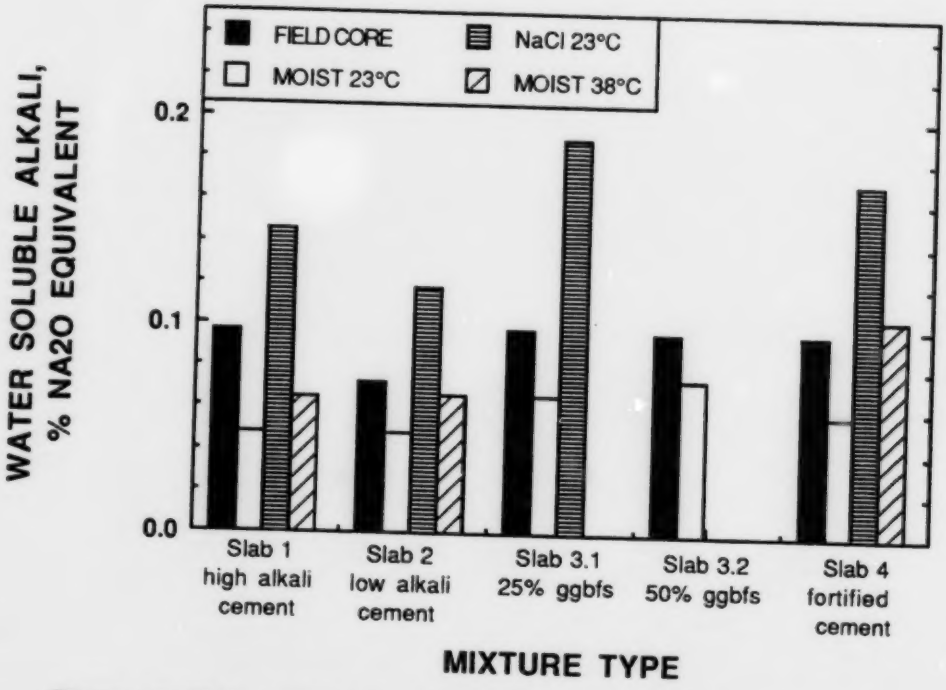

Figure 7 Water soluble alkalies remaining in the concretes after six years, expressed as Na_2O Equivalent

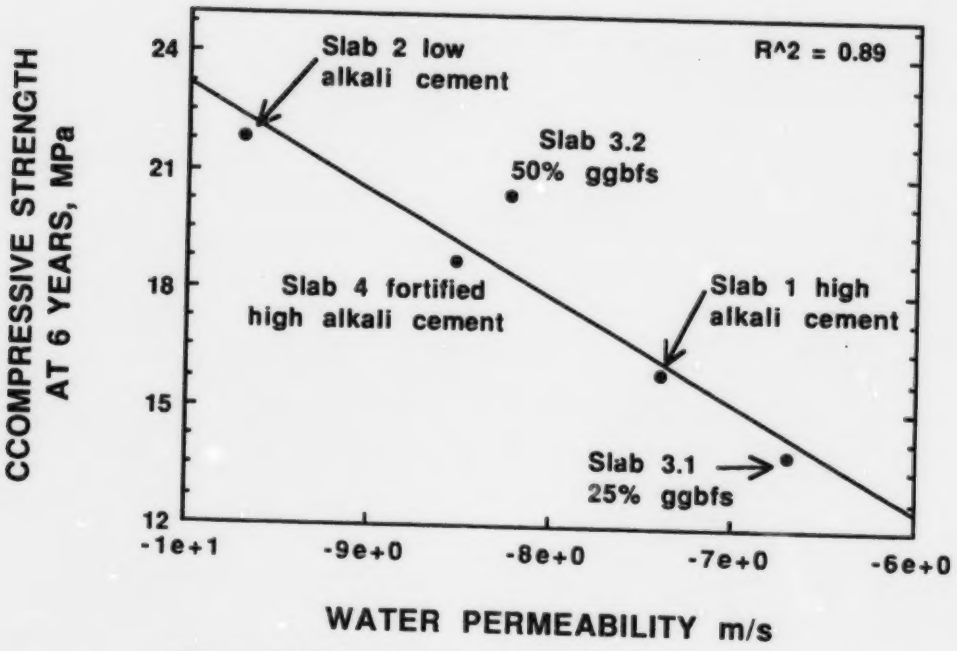

Figure 8 Compressive strength of concretes compared with water permeability after six years of outdoor exposure